

The resistivity of pore water solution—a decisive parameter of rebar corrosion and repair methods

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Although the resistivity of mortar and concrete is of major importance for rebar corrosion and repair methods, e.g. cathodic protection, there is a lack of fundamental research. This paper gives an overview of some of the more mechanistic aspects of the ionic conductance of mortar and concrete. It has been shown that not all water in mortar or concrete is conducting. The fractional volume of paste makes it possible to take into account the geometrically reduced cross-section of the conducting path due to the presence of aggregates. The influence of the pore structure of the paste itself and the chemical and physicochemical interactions of the water with the cement paste surface is much stronger than the geometrical effects. The combination of the above mentioned factors leads to an overall formation factor between the resistivity of concrete/mortar and the pore water in the paste of about 900 to 5000. The moisture content is much more important for the resistivity as well as for the corrosion rate than the chloride content. Copyright © 1996 Elsevier Science Ltd.

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The resistivity of mortar and concrete ρ_C is of major importance for rebar corrosion and repair methods. It is one of the factors controlling corrosion propagation (Figures 1(a) and (b)¹). At lower relative humidities (RH), i.e. at lower moisture content of the concrete, the corrosion current density i_{Corr} is approximately inversely proportional to the electrolyte resistance R_E and the resistivity ρ_C respectively or directly proportional to the conductivity σ_C according to Equation (1):

$$I_{\text{Corr}} \approx \frac{1}{R_E} \sim \frac{1}{\rho_C} = \sigma_C \quad (1)$$

The results of different studies²⁻⁴ have been analysed⁵ and are shown in Figure 2. The results shown in this figure are in good agreement with Gonzalez *et al.*⁶. Although the scatter is obviously large this type of information may be of great help in practice where one has to determine the corrosion risk and the corrosion propagation as well as to judge about the effect or efficiency of repair methods, e.g. after the application of coatings on concrete surfaces.

The resistivity of concrete is also of fundamental interest for cathodic protection because it mainly governs the current distribution between anode and cathode^{7,8} and it may drastically change in inhomogeneously humid concrete structures (Figure 3). Although the importance of the resistivity is generally

accepted, there have been only a small number of systematic and long-term studies on the resistivity of concrete and, specifically, its dependence on the relative humidity. Investigations on the pore water resistivity are very rare^{9,10}. These aspects will be discussed later.

At very high RH values the cathodic reaction dominates the corrosion process due to the O_2 depletion. In concrete with a high moisture content the diffusion coefficient of O_2 $D(O_2)$ is very low since O_2 has to diffuse through the water in the pores which is a much slower process than in the empty, airfilled pores. In water $D(O_2)$ is approximately four decades lower than in air ($\approx 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ in water compared to $\approx 0.2 \text{ cm}^2 \text{ s}^{-1}$ in air). An attempt has been made⁵ to calculate the diffusion coefficient of O_2 in concrete $D(O_2, C)$ as a function of the moisture content of the concrete. The curves in Figure 4 are primarily dependent on the porosity (which determines the vertical position) and the adsorption isotherm (which determines the shape). For the calculation it was assumed that the effective $D(O_2)$ in concrete is reduced by a factor of 10^2 to 10^4 compared to values in free air or water. The water content was taken from the adsorption isotherm in Figure 5. The curves shown in Figure 4 are basically in agreement with experimental results¹¹⁻¹⁴. It should be pointed out that for a given concrete this type of calculation can only be carried out if the adsorption isotherm

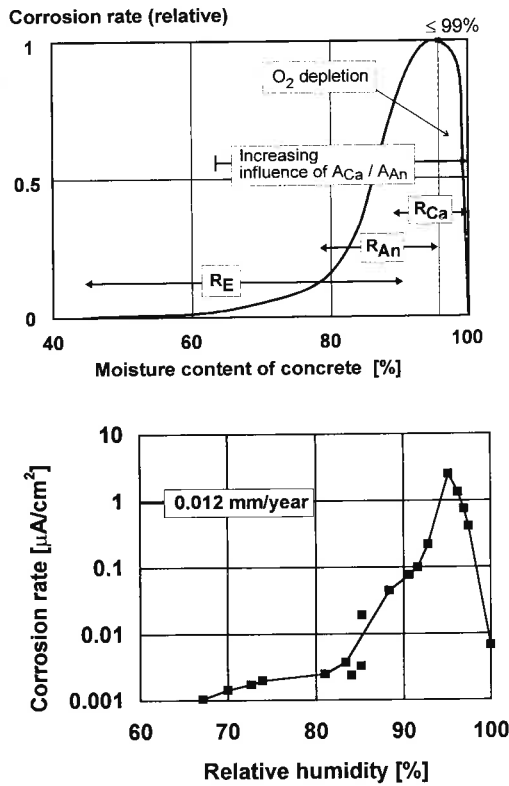


Figure 1 (a) Dependence of the corrosion rate on the water saturation and the dominant influence of the different resistances: R_{An} , electrochemical resistance of the anode; R_{Ca} , electrochemical resistance of the cathode; R_E , electrolyte resistance of the concrete/mortar; A_{An} , area of the anode; A_{Ca} , area of the cathode. (b) Corrosion of steel in carbonated mortar¹

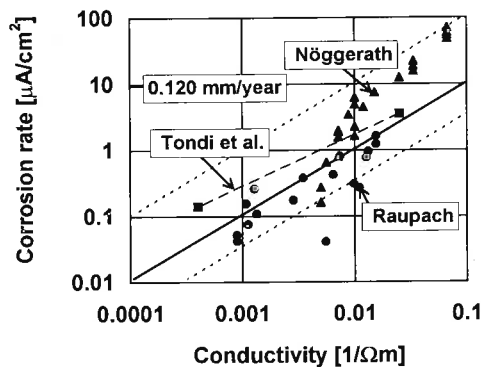


Figure 2 Corrosion rate as a function of the conductivity of concrete or mortar⁵

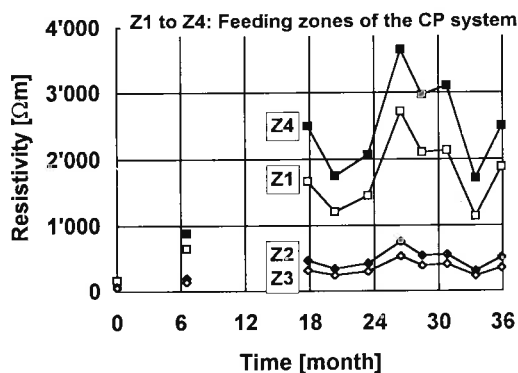


Figure 3 Concrete resistivity of different anode feeding zones of a cathodic protection system^{7,8}

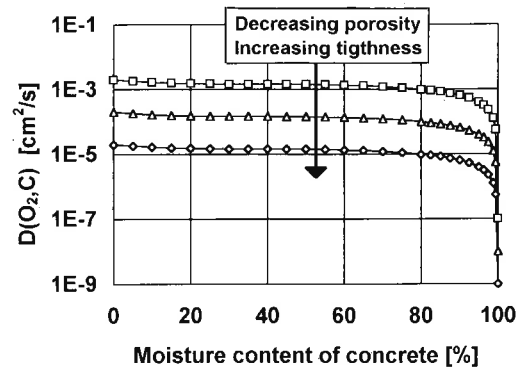


Figure 4 Diffusion coefficient of oxygen $D(O_2,C)$ as a function of the water saturation of concrete⁵

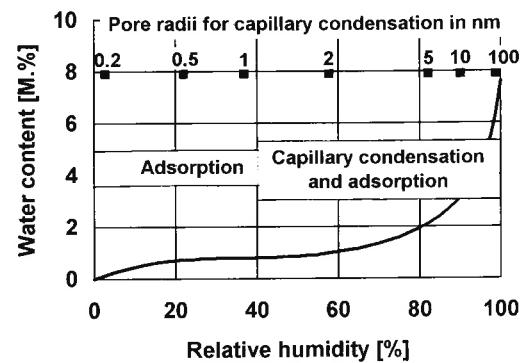


Figure 5 Typical adsorption isotherm of concrete⁵

of a specific concrete is known. Resistivity measurements may be of some help as will be shown later.

Adsorption isotherm

Porous materials such as mortar and concrete adsorb water from the air. The equilibrium of the water content of the porous material with the water content of the air (RH) is described by the adsorption isotherm. Figure 5 gives an example.

Up to a RH value of about 40% the uptake of water is a pure adsorption process. This water is not mobile, i.e. not free, but strongly bonded to the inner surface of the cement paste. At RH >40% additional water is taken up by capillary condensation. The forces attracting the capillary water are weak. The capillary pore water is, therefore, more or less free and mobile^{5,15}.

Resistivity of mortar and concrete

The resistivity ρ_C of mortar and concrete depends on the microstructure of the cement paste (pore volume, distribution of the pore radii), on the moisture and salt content and on the temperature^{5,15}. The microstructure is affected by various factors such as w/c ratio, binder content, degree of hydration, type and amount of additives such as micro silica or fly ash etc.

In an extensive investigation the resistivity of a variety of mortars has been measured up to almost two years¹⁵. The goal of this study was to evaluate conven-

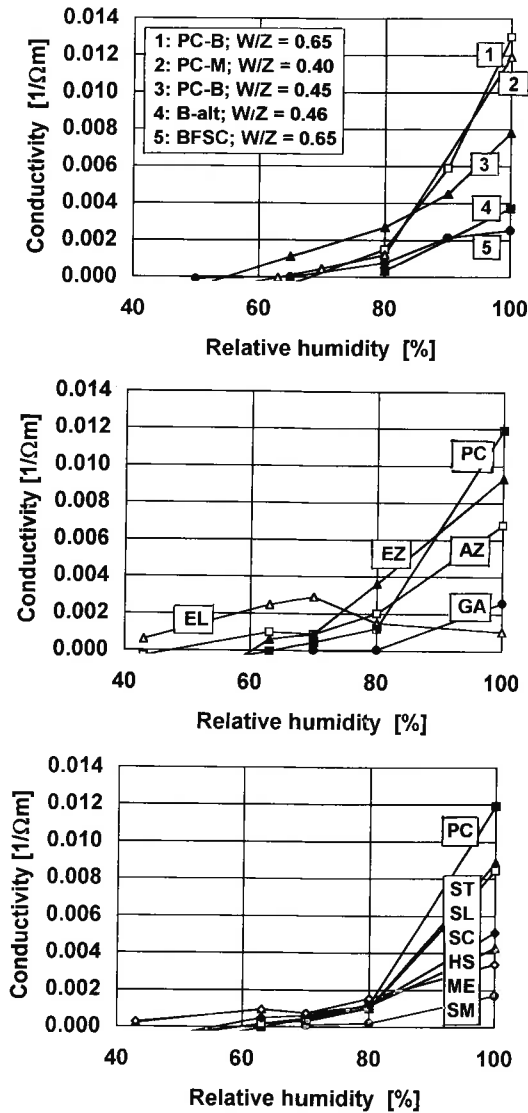


Figure 6 Dependence of the conductivity on the relative humidity of various mortars and concretes¹⁵: (a) PC-B, young OPC concrete; PC-M, young OPC mortar; B-alt, old OPC concrete; BFSC, young slag cement concrete. (b),(c) Young mortars¹: PC, OPC mortar²; SL, ST, SC, modified OPC mortar; AZ, EL, EZ, GA, HS, ME, SM, ready mix mortars

tional and ready mix mortars for cathodic protection systems. Samples of old concretes were included in this work as well as the results of another study¹⁶. Since the resistivities were still changing at the end of experiments the final values had to be extrapolated. Figures 6(a) to 6(c) show the final conductivity σ_c (= reciprocal value of the resistivity ρ_c) as a function of RH of different types of concrete and mortar. These σ_c -RH-curves reflect the different adsorption isotherms of the various materials. It is clearly visible in these figures that σ_c drastically decreases with decreasing RH and approaches zero at relative humidities between 40 and 80%.

For the PC concrete it may be concluded that the σ_c -RH curves are steeper the higher the w/c ratios are. Comparing the young and old concrete with the same w/c ratio the curve for the old concrete (B-alt) is shifted towards lower σ_c values. The shift is approximately parallel.

There is no general correlation between the resistivities and the total pore volume as was concluded from this study¹⁷. This is not surprising since not all the water in the pores is mobile.

The composition (cement, polymer and silica fume as well as additive and admixture content, w/c ratio, diameter of the aggregates etc.) of the mortars used in this study varied considerably. Details are given elsewhere^{15,17,18}. The mortar EL (Figure 6(b)) shows a somewhat surprising behaviour since the conductivity at RH = 70% is higher than at 100%. Most likely the pozzolanic reaction is stopped at RH < 80%, thus leading to a higher porosity at RH < 80% compared to RH = 100%.

The determination of the σ_c -RH curves might be used to determine the adsorption isotherm at higher relative humidities and the gel pore volume (see below).

Resistivity of pore water

In the above mentioned study^{15,17} the moisture content and porosity (total porosity, capillary and gel pore volume) was determined after the last resistivity measurement. From Figure 7 it may be seen that the conductivity of the OPC mortar approaches zero at RH of about 42% whereas the water content is still above 4 vol.%. It can be concluded that water remaining in the pores below this critical RH value, W^0 , is not conducting, i.e. not mobile.

Based on the assumption that W^0 is constant above the critical RH value it is possible to calculate the conducting amount of water W_{Cond} and the resistivity ρ_{PW} and conductivity σ_{PW} of the conducting pore water¹⁷:

$$\begin{aligned} \frac{1}{\rho_c} &= \sigma_c \approx \frac{1}{\rho_{PW}} \left(\frac{W_{tot} - W^0}{100} \right) = \frac{1}{\rho_{PW}} \left(\frac{W_{Cond}}{100} \right) \\ &= \sigma_{PW} \left(\frac{W_{Cond}}{100} \right) \end{aligned} \quad (2)$$

For the calculation of ρ_{PW} the value W^0 was fixed at the smallest standard deviation of ρ_{PW} . Smaller differences were noticed between the values at RH = 100%

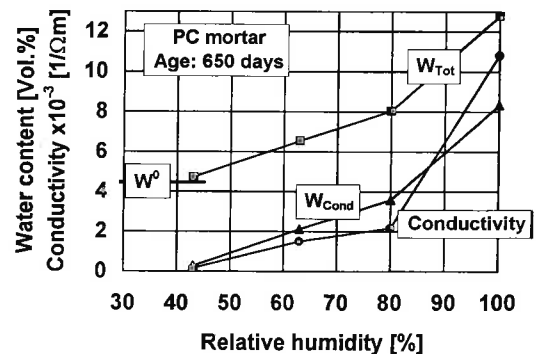


Figure 7 Total water content W_{Tot} , conducting water content W_{Cond} and conductivity as a function of the preceding storage humidity¹⁷

Table 1 Mean values and standard deviation (without the extreme values) of some characteristic numbers of the mortars used^{15,17}

Mortar concrete	Pore volume, vol%				Dry density kg m ⁻³	Resistivity of the pore water, Ωm		Nonconducting water content	
	Total	Capillary	Gel	Air		ρ_{PW} (Eq.(2)) ^a	b_1 (Eq.(4a)) ^b	Vol%	M%
AZ	17.2 ± 0.5	5.4 ± 1.5	8.9 ± 1.4	2.9 ± 0.2	2171 ± 7	9.6 ± 0.1	14.8	8.1	3.7
EL	4.6 ± 0.9	1.3 ± 0.1	3.1 ± 0.9	0.2 ± 1.2	2264 ± 5	64.2 ± 2.6	85.2	1.8	0.8
EZ	15.7 ± 0.4	7.0 ± 0.8	6.8 ± 0.8	2.0 ± 0.4	2198 ± 14	8.6 ± 0.7	11.5	6.8	3.1
ME	23.2 ± 0.3	7.5 ± 2.0	11.9 ± 2.0	6.5 ± 4.6	2010 ± 2	30.9 ± 1.0	37.7	10.4	5.2
PC	14.5 ± 0.4	6.5 ± 1.2	5.8 ± 0.8	2.2 ± 0.4	2283 ± 4	7.8 ± 0.8	5.1	4.5	2.0
SC	14.7 ± 0.2	5.7 ± 0.8	6.6 ± 0.8	2.3 ± 0.4	2269 ± 2	13.2	11.9	5.1	2.3
SL	13.5 ± 2.1	5.5 ± 1.5	5.9 ± 0.8	2.2 ± 0.3	2254 ± 3	9.3 ± 0.2	7.2	4.4	2.0
ST	9.2 ± 2.3	4.2 ± 0.7	3.6 ± 0.6	1.4 ± 2.3	2242 ± 2	8.4	6.9	4.5	2.0
HS	11.0 ± 1.2	5.1 ± 0.5	7.4 ± 1.9	-1.4 ± 0.7	1860 ± 5			6.1	3.3
GA	53.6 ± 1.0	33.3 ± 3.5	1.6 ± 0.6	18.7 ± 4.3	1253 ± 25	22.8 ± 2.2		3.0	2.4
SM	27.1 ± 1.9	6.0 ± 0.5	10.4 ± 0.7	10.6 ± 3.0	1438 ± 8	30.4 ± 1.3		10.5	7.3
PC 300 alt	10.1 ± 0.8	5.6 ± 0.4	3.0 ± 0.2	1.5 ± 0.3	2411 ± 20	14.9 ± 4.8	15.1	3.4	1.4

^a Values are given for RH = 100%

^b Calculated according to Equation (4a) for $\Phi_1 = 1$, $m = -1.96$ (see Figure 12)

and $RH \leq 80\%$. Therefore, ρ_{PW} was recalculated for $RH = 100\%$ and for $RH \leq 80\%$. Table 1 contains all the relevant data. Figure 8 shows the conducting water content W_{Cond} and Figure 9 the resistivity of the pore water as a function of RH. The behaviour of some of the ready mix mortars (HS, EL) is obviously rather strange. Very likely this is due to the difficult analysis of the porosity of these very dense mortars and thus rather erroneous results. The mortar ME has specifically been developed as overlay materials for cathodic protection systems.

For various mortars the average ρ_{PW} value is about $15 \pm 4 \Omega m$ for $RH \leq 80\%$ and $9 \pm 2 \Omega m$ for $RH = 100\%$. There are various possible reasons causing the lower resistivity value of the pore water at $RH = 100\%$:

- The pore water in the larger capillaries, only filled with water at very high relative humidities, is more mobile than the water in the smaller capillaries.
- The same might be true for water in the interface between cement paste and aggregate.

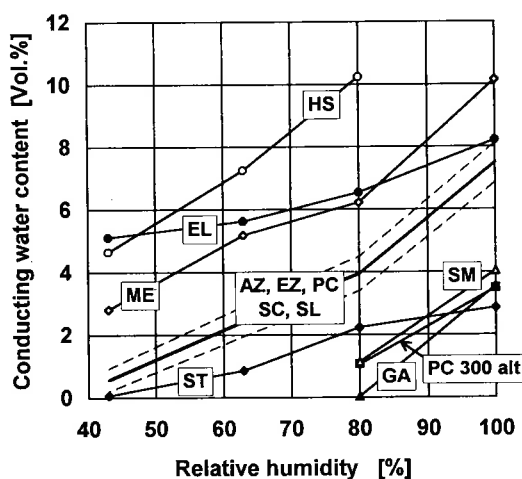


Figure 8 Conducting water content W_{Cond} as a function of the preceding storage humidity of a variety of mortars and an old concrete (PC 300 alt). For some mortars only the average \pm standard deviation is given¹⁷

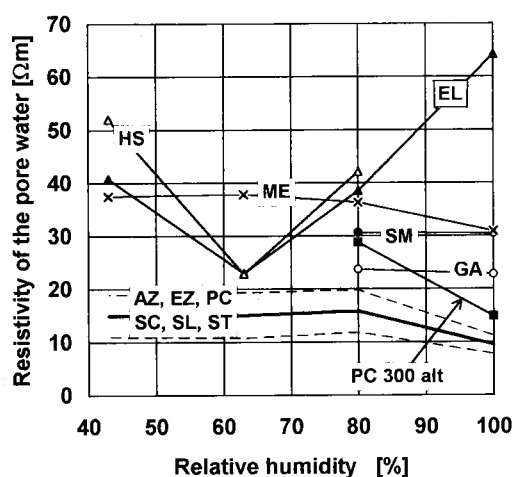


Figure 9 Pore water resistivity as a function of the preceding storage humidity of a variety of mortars and an old concrete (PC 300 alt). For some mortars only the average \pm standard deviation is given¹⁷

- At high humidities practically no carbonation takes place compared to mortar exposed to a less humid atmosphere. Carbonation at lower relative humidities reduces the OH^- concentration and results in a higher resistivity of the pore water.

The ρ_{PW} value of the old concrete is about a factor of 1.5 to 2 higher than those of the young mortars. This finding might also be explained by the carbonation of the pore water. Additionally the pore structure could have some influence. The findings presented above do allow a rough estimation of the resistivity of wet mortars and concrete provided the capillary pore volume is known.

It has already been stated that the nonconducting water represents the water strongly bonded to the cement paste surface. It is, therefore, not surprising that the nonconducting water content approximately corresponds to the volume of the gel pore (Figure 10).

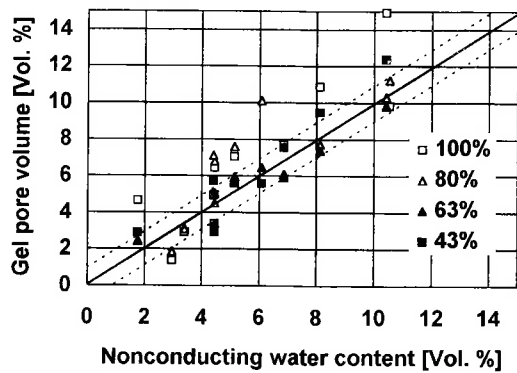


Figure 10 Relation between gel pore volume and nonconducting water content after storage at different relative humidities¹⁷

Pore water analysis and pore water resistivity

Although there are some objections about the pore water expression technique because of the destruction of the pore structure and other reasons¹⁹ it is the only way to a direct analysis of the pore water composition. By means of this technique it has been found that the composition depends e.g. on the age of the paste, the type, amount and origin of the cement used as well as on the w/c ratio^{9,10,20-28}. The major components of the pore liquid are K^+ , Na^+ and OH^- and to a much lower extent Ca^{2+} and SO_4^{2-} . The average ionic strength of the pore water (mainly K^+ and Na^+ with a corresponding amount of OH^-) of chloride-free ordinary cement paste and mortar or concrete ranges from 0.3 to 0.7 mol l⁻¹ (corresponding to a pH of about 13.5 to 13.8) depending mainly on the alkali content of the cement.

One of the first papers which dealt with the resistivity of the pore water ρ_{PW} was published by Catharin and Federspiel⁹. They determined the pore water resistivity of 20 min old cement paste and found values between 0.2 and 0.3 Ωm . Many years later it could be shown that the pore water resistivity changes with time and, as expected, with the pore water composition^{10,29}. Christensen *et al.*¹⁰ observed at the very beginning ρ_{PW} values around 0.25 Ωm and then in the first 100 h a drastic decrease (corresponding to the increase of the ionic strength). Whereas ρ_{PW} of the silica fume paste steadily increased after that time, ρ_{PW} of the OPC paste decreased further and reached at about 500 h a constant value of approximately 0.06 Ωm . Much higher values for ρ_{PW} were determined by Buenfeld *et al.*²⁹ for OPC mortar with w/c ratios of 0.4 and 0.6 respectively. They found ρ_{PW} values between 0.3 and 0.4 Ωm with only a little change over the time range from 4 to 20 weeks. The cement composition, i.e. the different alkali content, might be one of the possible reasons for the differences between these investigations.

The pore water resistivities mentioned above are significantly lower than that of freshly saturated (1.2 Ωm) or a saturated but carbonated $Ca(OH)_2$ solution (5.5 Ωm)¹⁷.

Pore water analysis was also carried out with chloride contaminated cementitious materials^{22,26,27,30,31}. Chloride concentrations in the pore water up to 3.5 mol l⁻¹ were found. Unfortunately there are no reports so far on the

resistivity of chloride containing pore water. Because of this lack of data synthetic pore water solutions were prepared and analysed. Figure 11 shows the results of different solutions with NaCl addition from 0 to 5 mol l⁻¹: saturated $Ca(OH)_2$, 0.3 mol l⁻¹ KOH + 0.1 mol l⁻¹ NaOH and 0.5 mol l⁻¹ KOH + 0.2 mol l⁻¹ NaOH. From this figure it is concluded that the influence of the chloride concentrations on the resistivity of the pore water strongly decreases with increasing alkali content of the cement and of the pore water, respectively.

Comparison between resistivity of concrete and pore water

Concrete is a composite of particles of aggregate of various size in a matrix of cement paste. Since the resistivities of the aggregate are several orders of magnitude higher than that of the water in the pores it can be concluded that concrete can be considered as being non-conducting aggregate particles embedded in an ionically conducting cement paste matrix. For specific arrangements of regularly shaped aggregates, it is possible to calculate the resistivity taking into account the volume of the aggregate as well as the volume and the resistivity of the conducting water³². With these assumptions the term Formation Factor F can be adopted^{29,32,33}. Then the following equations can be written:

$$F_1 = \rho_C / \rho_P = a_1 (\Phi_1)^{-m} \quad (3a)$$

$$F_2 = \rho_C / \rho_{PW} = a_2 (\Phi_2)^{-m} \quad (3b)$$

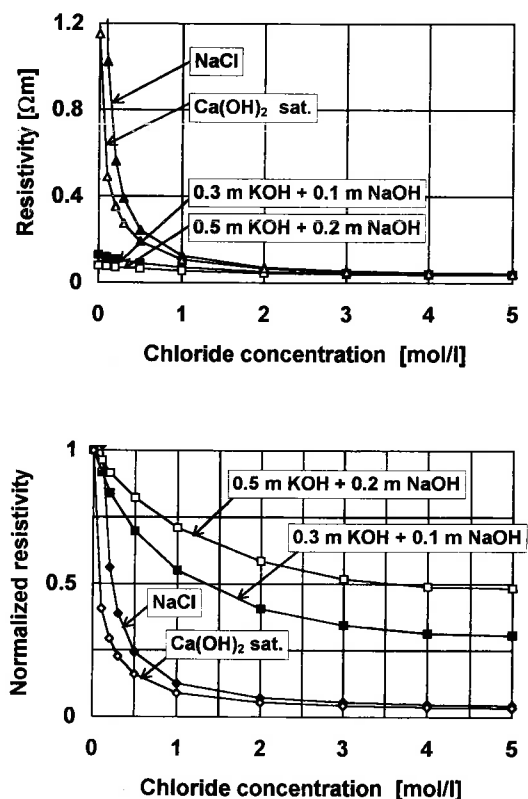


Figure 11 (a) Dependence of the resistivity of synthetic pore water solutions on the chloride concentrations, and as comparison, the curve for pure NaCl solutions. (b) As (a), normalized resistivity

where a_1 and a_2 are constants, ρ_C , ρ_P , and ρ_{PW} the resistivity of the concrete, paste and pore water and Φ_1 is the volume fraction of the cement paste within the concrete and Φ_2 the volume fraction of the aggregate and of the non-conducting part of the cement paste, respectively. The fractional volume Φ_1 can be calculated according Equation (3c):

$$\Phi_1 = 1 - (M_A/d_A) \quad (3c)$$

where M_A is the mass and d_A the density of the aggregate ($d_A = 2700 \text{ kg m}^{-3}$). There is no formula to calculate fractional volume Φ_2 .

If ρ_P and ρ_{PW} can be assumed to be constant for a given set of conditions Equations (3a) and (3b) can be rewritten³³:

$$\rho_C = b_1 (\Phi_1)^{-m} \quad (4a)$$

$$\rho_C = b_2 (\Phi_2)^{-m} \quad (4b)$$

By means of impedance spectroscopy, McCarter *et al.*³³ found in a parametric study that the bulk resistivity ρ_C of both mortars and concretes is almost entirely dependent upon the fractional volume of cement paste within the mix. Increasing the aggregate content had the effect of reducing the cross-sectional area of the conduction phase. For OPC mortars and concretes one hour after mixing (paste still in the plastic state) they found for the constants in Equation (4a) the following values: $b_1 = 0.919 \text{ } \Omega\text{m}$ and $m = -1.96$. For pure OPC cement paste they found resistivity values between 0.81 and 0.86 Ωm . These values are in the same range as those of Catharin *et al.*⁹ measured 20 min after mixing (0.45 to 0.86 Ωm).

Figure 12 shows the results of the work of McCarter *et al.*³³ as well as the results of the above mentioned study^{15,17}. Because not all details of some ready mix mortars were accurately known, the fractional volume of the paste had to be estimated for these mortars using the cement content and the w/c ratio. For some other mortars an assumption had to be made for the cement and/or the w/c ratio. Using the slope of McCarter's study³³ one can extrapolate the resistivity at $\Phi_1 = 1$ for the very different and much older mortars and the old

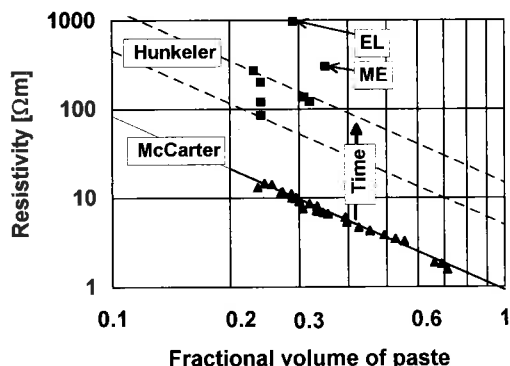


Figure 12 Resistivity of a variety of mortars and concretes versus fractional volume of the cement paste according to Equation (4a). Age of the materials: McCarter³³, 1 hour; Hunkeler^{15,17}: >>2 years

concrete investigated^{15,17}. It is striking to note that the values at the intersection with the y-axis for $\Phi = 1$ are almost identical with the values calculated using Equation (2) (Table 1). It seems that the slope of the curve in Figure 12 is independent of the age, at least if the materials are older than 1 h. It has been further mentioned³³ that this slope remained the same for mixes with sulphate resisting Portland cement. The parallel shift to higher resistivities with time is due to structural changes within the cement paste (increase of the nonconducting portion of the paste).

The approach of McCarter *et al.*^{32,33} is very useful but with the fractional volume of paste only the geometrical effects of the restricted conductance through mortar and concrete due to the aggregates are considered. The resistivity of the pore water is affected, additionally, by the structure of the paste itself (roughness of the pores, pore radii and pore size distribution) as well as by chemical and physicochemical interactions of the ionic species with the cement paste surface (e.g. adsorption and chemisorption). Comparing now the values of the resistivity of the bulk pore water (0.06 Ωm was taken as the most reliable value, Figure 11) with the real pore water resistivity ρ_{PW} of about 5 to 15 Ωm measured on older mortars and concretes at RH = 100% leads to a ratio $\rho_{PW}(\text{concrete})/\rho_{PW}(\text{bulk})$ in the range between 80 to 250 (the strongly modified ready mix mortars were not considered here). These values are about one order of magnitude higher than the geometrical effect of the aggregates for a fractional volume of paste between 0.2 and 0.3 (Figure 12). Thus, the formation factor F_2 ranges between about 900 and 5000. These values are much higher than those determined by Buenfeld *et al.*²⁹. This is partly due to the fact that a much higher resistivity of the expressed pore water had been used in their calculation. The values of F_2 found here are similar to the reduction of the permeability (Figure 4).

Based on what has been said above, the higher resistivities of concretes containing pozzolanic materials compared to those without addition can be explained by higher values of F_2 due to the higher pore water resistivities (lower ionic strength) and the lower fractional volume of the conduction phase.

Finally, it has to be pointed out that carbonation of the pore water leads to higher resistivities (see above). Catharin *et al.*⁹ found for carbonated pore water about a factor of 1.3 to 2 higher resistivities than those of uncarbonated pore water.

Influence of chloride

The influence of chloride on the resistivity of concrete and mortar has been investigated by very few authors³⁴⁻³⁷. Unfortunately extensive and systematic studies under more or less steady state conditions are not available yet. This is rather surprising with respect to the importance of the chloride-induced corrosion problems around the world. In Figure 13 some of the available results are summarized. Generally a tendency towards lower resistivities has been observed with

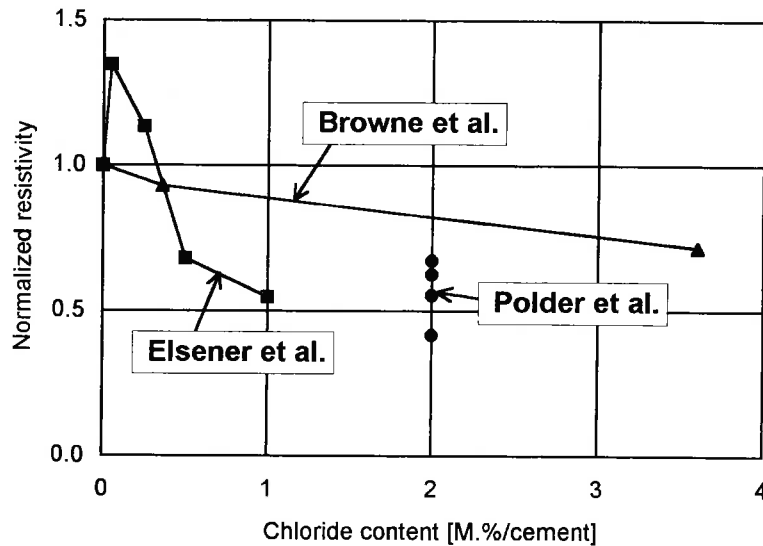


Figure 13 Relative change of the resistivity or resistance with the chloride content. Data from Browne *et al.*³⁴, Elsener *et al.*³⁵ and Polder *et al.*³⁶. Compare this figure with Figure 11b

increasing chloride content. High chloride contents between 1 and over 2 M%/cement reduced the resistivity by a factor between 2 and 3 at the maximum³⁴⁻³⁷.

Browne *et al.*³⁴ investigated a concrete with a chloride content of 0.45 M%/concrete. The chloride content of the pore water of this concrete is roughly estimated to about 2.3 mol l⁻¹ assuming a density of 2400 kg m⁻³ and total pore volume of about 5.5 M% or 13.2 vol%. But the resistivity was only reduced from about 9 to about 6 Ωm, i.e. some 27%. For the concrete with a chloride content of 0.045 M%/concrete the reduction of the resistivity is about 7%. Interestingly, the reduction does obviously not depend on the moisture content of the concrete as Browne *et al.*³⁴ found.

This quite small effect of high chloride concentrations is not very surprising since the pore water resistivity is rather low even before the chlorides are brought into the pore solution (Figures 11a and b).

It has to be pointed out that the pH of Ca(OH)₂ solution decreases with increasing NaCl content and reduces, therefore, the Ca²⁺ and OH⁻ ion content (Figure 14). For the 2.5 molar NaCl solution the pH is reduced to about 12. Similar trends have been observed

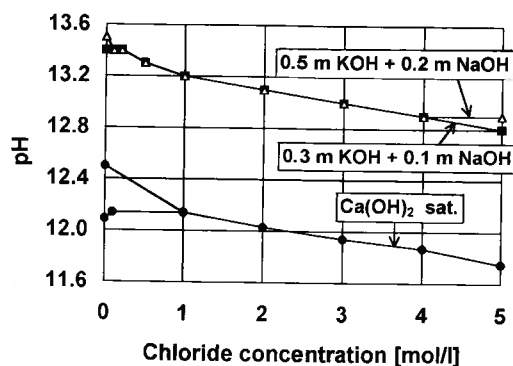


Figure 14 Dependency of the pH of synthetic pore water solutions on the NaCl concentration

for the KOH + NaOH solutions. Thus, the increase of the conductivity with increasing chloride content is counteracted by the simultaneous reduction of the OH⁻ concentration in the pore water.

Summary and conclusions

Although the resistivity of mortar and concrete is of major importance for corrosion and repair methods there is a lack of fundamental research. This paper tried to give an overview of some of the more mechanistic aspects of the ionic conductance of mortar and concrete. But more fundamental research is needed for a better understanding.

It has been shown that not all water in mortar or concrete is conducting. The nonconducting water is probably the water kept in the gel pores or adsorbed, i.e. strongly bonded to the surface of the cement paste.

The fractional volume of paste makes it possible to take into account the geometrically reduced cross-section of the conducting path due to the presence of aggregates. This model makes it possible to roughly extrapolate the resistivity of the pore water in the cement paste. Reducing the fractional volume of paste from 1 (pure cement paste) to about 0.2 to 0.3 for common mortars and concrete leads to an increase of the resistivity by a factor of about 10 to 20.

The influence of the pore structure of the paste itself and the chemical and physicochemical interactions of the water with the cement paste surface is much stronger than the geometrical effects. But there is no model taking into account these effects. Results of the analysis of the pore water expressed from mortars and concretes were compared with results of resistivity measurements. It has been found that the expressed (bulk) pore water is about a factor of 80 to 250 more conducting than the water in the pores.

The combination of the above factors leads to an overall formation factor between the resistivity of

concrete/mortar and the pore water in the paste of about 900 to 5000.

As a consequence of the very low resistivity of the pore water the influence of even high chloride contents on the resistivity of mortars and concretes is rather small. This is important and leads to the conclusions that the moisture content is much more important for the corrosion rate than the chloride content. This is indeed an important feature for the designing of cathodic protection systems, too.

The overwhelming effect attributed to the paste structure itself (and not to the geometrical effects due to the aggregates) explains the different behaviour of mortar and concrete containing slag, silica fume or fly ash^{29,33}. Very likely this is due to the pozzolanic reaction which takes place after setting and might last for a long period of time whereas the pore water composition and paste structure of OPC does mainly change during the first few weeks and much less thereafter.

Resistivity measurements might give another approach to permeation and diffusion processes³⁸. The advantage of the resistivity measurements is that they are easy to carry out and the moisture content of the material does not cause the same problems as for other methods which are in use to characterize cementitious materials.

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